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Cue contrast modulates the effects of exogenous attention on appearance

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ABSTRACT

Exogenous spatial attention can be automatically engaged by a cue presented in the visual periphery. To investigate the effects of exogenous attention, previous studies have generally used highly salient cues that reliably trigger attention. However, the cueing threshold of exogenous attention has been unexamined. We investigated whether the attentional effect varies with cue salience. We examined the magnitude of the attentional effect on apparent contrast [Carrasco, M., Ling, S., & Read, S. (2004). Attention alters appearance. *Nature Neuroscience*, *7*(3), 308–313.] elicited by cues with negative Weber contrast between 6% and 100%. Cue contrast modulated the attentional effect, even at cue contrasts above the level at which observers can perfectly localize the cue; hence, the result is not due to an increase in cue visibility. No attentional effect is observed when the 100% contrast cue is presented after the stimuli, ruling out cue bias or sensory interaction between cues and stimuli as alternative explanations. A second experiment, using the same paradigm with high contrast motion stimuli gave similar results, providing further evidence against a sensory interaction explanation, as the stimuli and task were defined on a visual dimension independent from cue contrast. Although exogenous attention is triggered automatically and involuntarily, the attentional effect is gradual.

1. Introduction

At any given time, we are able to process only a portion of the vast amount of visual information in our environment. Spatial attention selectively grants processing priority to a subset of information that may be behaviorally relevant. Attention usually coincides with foveation, but one can also covertly attend to locations in the periphery without moving the eyes (Posner, 1980). Covert attention has an endogenous, voluntary component and an exogenous, automatic component (Cheal & Lyon, 1991; Jonides & Yantis, 1988; Nakayama & Mackeben, 1989; Posner, 1980).

Exogenous covert attention selectively prioritizes spatial locations in the visual field, leading to enhanced visual processing (Carrasco, Giordano, & McElree, 2004, 2006; Carrasco & McElree, 2001), improves performance in perceptual tasks (Baldassi & Verghese, 2005; Carrasco & McElree, 2001; Carrasco, Penpeci-Talgar, & Eckstein, 2000; Carrasco, Williams, & Yeshurun, 2002; Dosher & Lu, 2000; Lu & Dosher, 1998, 2000; Nakayama & Mackeben, 1989; Smith, Wolfgang, & Sinclair, 2004; Talgar, Pelli, & Carrasco, 2004), and imposes perceptual "costs" at unattended locations (Montagna, Pestilli, & Carrasco, 2009; Pestilli & Carrasco, 2005; Pestilli, Viera, & Carrasco, 2007). Exogenous attention also changes some aspects of subjective appearance at the attended location, e.g. contrast (Carrasco, Fuller, & Ling, 2008; Carrasco et al., 2004; Fuller, Rodriguez, & Carrasco, 2008; Hsieh, Caplovitz, & Tse, 2005; Ling & Carrasco, 2007), spatial frequency (Gobell & Carrasco, 2005), motion coherence (Liu, Fuller, & Carrasco, 2006), flicker rate (Montagna & Carrasco, 2006), speed (Turatto, Vescovi, & Valsecchi, 2007) and size (Anton-Erxleben, Henrich, & Treue, 2007) of moving patterns, and color saturation but not hue (Fuller & Carrasco, 2006).

Endogenous shifts of covert attention are under the voluntary control of the observer. Deployment of endogenous attention can be cued to a peripheral location by a symbolic cue at another location in the visual field. In experimental paradigms, for example, a foveal cue indicating the location of an upcoming target can provide relevant information to help the observer perform the task, facilitating a shift of the observer's locus of attention to that location. Because the shift is voluntary, the validity of the information provided by the cue is important. A cue that accurately predicts the target location on 100% of trials is likely to be heeded. However, if the cue is only accurate at chance, and is therefore of no systematic use in performing the task, observers can easily ignore it and choose another strategy.

By comparison, exogenous cues "draw" the deployment of spatial attention to their general location in the visual field, and there appears to be no voluntary effort required by the observer to accomplish the deployment. There is, however, substantial

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evidence that endogenous and exogenous attention interact. The efficacy of an exogenous cue can be constrained by highly focused endogenous attention at another location (Theeuwes, 1990; Yantis & Jonides, 1984, 1990), or when the task is defined on a target feature that is not shared by the exogenous cue (Folk, Remington, & Johnston, 1992). It appears to be possible that under some circumstances involuntary, exogenous reorienting may be more capable of overriding such voluntary constraints, e.g. as the eccentricity of the exogenous cue increases (Van der Lubbe & Postma, 2005). Another important characteristic of exogenous attention is that the cues need not be informative for the attentional shift to occur (e.g. Liu, Pestilli & Carrasco, 2005; Pestilli et al., 2007), and that the magnitudes of exogenous attention effects on contrast sensitivity with fully informative and non-informative cues are comparable (Cameron, Tai & Carrasco, 2002; Carrasco et al., 2000; Pestilli & Carrasco, 2005). Moreover, exogenous cues exert an effect even when deployment of attention impairs observer performance (Talgar & Carrasco, 2002; Yeshurun, 2004; Yeshurun & Carrasco, 1998, 2000) and it would be beneficial if observers could ignore the cue.

Recent studies have compared the automaticity and flexibility of the effects of exogenous and endogenous attention. For instance, a study on texture segmentation revealed that whereas the former improves or impairs performance as a function of target eccentricity, the latter improves performance throughout the visual field (Yeshurun, Montagna, & Carrasco, 2008). More relevant for the present study, studies manipulating cue validity have shown that for endogenous attention, the magnitude of the effects of the performance benefit at the cued location and the performance cost at the uncued locations, brought about by valid and invalid cues, respectively, scale with cue validity (Giordano, McElree & Carrasco, 2009; Kinchla, 1980; Sperling & Melchner, 1978; Vossel, Theil, & Fink, 2006). However, for exogenous attention, the magnitude of the performance benefit and cost are not affected by cue validity (Giordano et al., 2009). These two studies clearly indicate that whereas endogenous attention is flexible exogenous attention is automatic.

The literature on exogenous attention is replete with studies on what constitutes a cue for exogenous attention. Whereas initial explanations proposed that the cueing mechanism operates on high-level representations, i.e. after identification of objects (Hillstrom & Yantis, 1994; Jonides & Yantis, 1988; Yantis, 1993; Yantis & Hillstrom, 1994; Yantis & Jonides, 1996), an alternative explanation is that the sensory transients associated with the appearance of an object cause attentional capture. This transient hypothesis is supported by more recent findings that abrupt changes in luminance (Franconeri, Hollingworth, & Simons, 2005) or motion (Franconeri & Simons, 2003) of already visible objects engage attention. However, the applicability of search studies to questions regarding exogenous attention cues is somewhat limited by the nature of the task: the "cue" is itself a salient stimulus if not the target of the search.

Posner (1980) developed a widely used paradigm to study the effects of exogenous attention in which the cue is a box or frame that suddenly undergoes a large change in luminance, separate from and prior to the presentation of the task stimuli. Variations on this methodology have used different shapes, sizes, and other features to trigger attention at or near the cue location. The localization of exogenous attention permits stimuli to be presented inside or outside of its spatial envelope, to investigate the effects of attention on different aspects of visual perception. The main concern regarding cues in this line of research is that they reliably trigger attention. Generally, such cues have been high contrast dots, lines, boxes, and the like (e.g., Anton-Erxleben et al., 2007; Carrasco et al., 2004; Chastain & Cheal, 1999; Cheal & Lyon, 1991; Fuller & Carrasco, 2006; Fuller et al., 2008; Gobell & Carrasco, 2005; Montagna & Carrasco, 2006; Müller & Rabbitt, 1989; Pestilli & Carrasco, 2005; Posner, 1980; Turatto et al., 2007). Most experimental cues are created using luminance contrast, out of convenience and the relatively large luminance range of computer monitors.

Notwithstanding the numerous studies of the effects of exogenous attention on visual processing and perception, there has been relatively little investigation of how the physical properties of the cue affect the deployment of attention. Several studies have shown that luminance transients are not necessary for cues to be effective, and that chromatic cues isoluminant with the background are capable of triggering exogenous attention (Carrasco, Loula, & Ho, 2006; Gellatly, Cole, & Blurton, 1999; Lambert, Wells, & Kean, 2003; Snowden, 2002; Steinman, Steinman, & Lehmkuhle, 1997; Yantis & Hillstrom, 1994; Yeshurun & Carrasco, 1998, 2000). In a study measuring the spatial field of exogenous attention using the line motion illusion, the magnitude, spatial extent, and duration of the attentional effect with such chromatic cues was smaller than that of high contrast or low contrast luminance cues, but there was no difference between high and low contrast cue (Steinman et al., 1997). Based on these findings, the authors concluded that luminance is a more important driver for the exogenous cuing mechanism and that the magnocellular pathway may be its primary input.

To engage attention, exogenous cues need not even be sufficiently visible that observers are aware of them. McCormick (1997) compared reaction times for target detection using high contrast cues and low contrast peripheral cues. The low contrast cues were set so that observers were only able to report their presence on $\sim$3% of trials, and these trials were excluded from analysis. Reaction times were faster when the target appeared at the cued location relative to the uncued location for both high and low contrast cues. Mulckhuyse, Talsma, and Theeuwes (2007) investigated the effectiveness of subliminal cues by using a small temporal asynchrony between three place-holders in their display to automatically engage attention. In a separate task, they verified that observers could not report the location of the disc that appeared first at above chance. Their main target detection task showed a cueing effect that speeded RT for targets at the cued location for a short SOA between cue and target, with slowed RT at the cued location for a 1000 ms SOA (inhibition of return). These two studies, using reaction time in a detection task, showed that extremely low contrast cues, below the threshold of awareness, can be sufficient to engage exogenous attention. They did not, however, establish whether the magnitude of attentional effects, when engaged by subliminal cues, is comparable to effects with suprathreshold cues.

The evidence for automaticity and the effectiveness of even subliminal cues suggests an exogenous cueing mechanism that is fairly inflexible. A reader of the literature could easily infer that such effects are "all-or-nothing", that the magnitude of the attentional effect is uniform. However, methological differences across studies pose a difficulty for comparing the magnitude of attentional effects, and the question of whether the magnitude may vary across some range of physical cue intensities has not been systematically investigated.

The present study examines whether exogenous attention effects for luminance cues scale with cue contrast, across a broad range of cue contrasts from imperfectly visible (i.e. below the objective threshold of spatial localization) to 100% contrast. Our dependent measures of exogenous attention are the magnitude of change in apparent contrast elicited by attention (Carrasco et al., 2004, 2008; Fuller et al., 2008; Hsieh et al., 2005; Ling & Carrasco, 2007), and in a second experiment the change in apparent speed of moving high contrast Gabors (Turatto et al., 2007). We chose to investigate appearance on these dimensions because of the relatively large appearance effects that have been reported. We have elsewhere suggested (Fuller et al., 2008) that the appearance paradigm used in these studies may be a more sensitive task with which to measure the effects of exogenous attention than discrimination performance tasks on a single target. The appearance task involves a comparative judgment between one stimulus that accrues the perceptual "benefit" of spatial attention and another that bears the "cost" of being outside the locus of attention (Montagna et al., 2009; Pestilli & Carrasco, 2005; Pestilli et al., 2007), whereas performance in discrimination tasks (e.g. orientation discrimination) measure the effect of attention at a single target location. In Fuller et al. (2008) we developed a SDT model of the appearance and orientation discrimination tasks, demonstrating how the greater sensitivity of the appearance task may arise. We use the appearance task in the present study because it may provide greater ability to detect scaling in the effects of exogenous attention with cue contrast.

2. Experiments

2.1. General methods

2.1.1. Apparatus

The experiments were programmed using the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) and Matlab R2007A, running on an Apple iMac computer. Observers viewed the experimental display on a second monitor, a 20 in. IBM P260, at 1280×1024 pixel resolution at a 100 Hz refresh rate. The monitor was characterized with a PR650 spectrophotometer; for the experiment the video card lookup table was linearized for luminance, with 10-bit color specification and a maximum luminance of $\sim$26 cd/m^2. Participants sat in a dark room 57 cm from the monitor. Head position was controlled with a chin rest. Observers were instructed to maintain fixation at the central fixation point.

2.1.2. Subjects

The observers in Experiment 1 were six undergraduate and graduate students recruited from the New York University Psychology Department. Four were female and two were male, with a mean age of 28. Two observers (SF and YP) were authors, and the other four participants were naive as to the purpose of the experiment. Five observers participated Experiment 2, four of whom had participated in Experiment 1 (including one author, YP). Four observers were female, one male, with a mean age of 25. All observers had normal or corrected to normal vision.

2.1.3. General procedure

The experiments were each conducted in three stages. The specific stimuli, display elements, timing, and procedures for each are detailed in the in specific sections for Experiments 1 and 2. The following explains the general structure and rationale that applies to both experiments.

2.1.3.1. Preliminary task session.

- *Localization of single peripheral cues*. Estimate observers' psychometric functions for *localization of single peripheral cues* as a function of cue contrast, at the cue locations used in the appearance task. This was important to rule out that any scaling of the appearance effect with cue contrast was due to near-threshold or inconsistent visibility of the cues.
- *Localization of stimuli*. Test observers' in Experiment 1, which used a range of Gabor stimulus contrasts, to verify their *ability to localize all the stimuli* at the peripheral locations used in that experiment with >95% correct performance.
- *Practice appearance task*. Train observers in the appearance task using the easiest of the stimulus pairs to judge (Standard and highest Test contrast in Experiment 1; Standard and fastest Test speed in Experiment 2) with audio feedback for correct responses. In Experiment 1, we additionally used QUEST staircases (Watson & Pelli, 1983) during this training to titrate the stimulus tilt from vertical to equate starting difficulty of the orientation discrimination to 80% correct performance.

2.1.3.2. Main appearance task sessions. We assessed the effects of cue salience on the magnitude of the change in stimulus appearance. We used the task developed by Carrasco et al. (2004): observers reported stimulus feature A (orientation in Experiment 1, motion direction in Experiment 2) for the stimulus that was higher in stimulus feature B (contrast in Experiment 1, faster speed in Experiment 2). Exogenous attention was deployed to one of the two nearby stimulus locations by an uninformative peripheral cue, and compared to a "neutral" condition in which the cue appeared at fixation. Cue contrast randomly varied among pre-selected values in both experiments. This task was run in six 1-h sessions for Experiment 1, and three 1-h sessions for Experiment 2.

2.1.3.3. Control task session. The final session was a control experiment identical to the main appearance task in all respects, except that the cue appeared after the stimuli and cue contrast was fixed at 100%. The logic of this control was that exogenous attention would be deployed to the peripherally cued locations after stimulus presentation, and therefore would not affect observers' perceptions of the stimuli. Perceptual interaction between the peripheral cues and stimuli, as well as response-bias elicited by the cue, may still remain, if they were present in the main appearance task. This control has been used in studies of perceived contrast (Carrasco et al., 2008), as well as perceived spatial frequency (Gobell & Carrasco, 2005), color saturation (Fuller & Carrasco, 2006), flicker rate (Montagna & Carrasco, 2006), size of a moving object (Anton-Erxleben et al., 2007), and speed (Turatto et al., 2007).

2.2. Experiment 1: contrast

2.2.1. Stimuli and cues

The stimuli were Gabor patches (5 cpd spatial frequency; $4^\circ \times 4^\circ$ with the width of the Gaussian envelope at half height $\sim 1^\circ$) located at 7° eccentricity left or right of the center fixation point. The Gabor stimuli varied in Michelson percent contrast: 10%, 12.6%, 17.8%, 22.4%, 28.2%, 35.5%, 44.7%, 56.2%, and 79.4%, spaced in equal log-contrast intervals. The cues were horizontal bars ($1.25^\circ \times 0.4^\circ$) that ranged in negative Weber contrast: 6%, 9%, 12%, 25%, 50%, 75%, and 100% (the maximum-contrast cue was black). Cue locations were centered 3° directly above the two stimulus locations, and at fixation. The fixation point was a 0.15° dot, luminance $\sim$1 cd/m^2. The background luminance was 10 cd/m^2.

2.2.2. Specific procedures

2.2.2.1. Peripheral cue localization. Trials began with fixation on the central point for 750 ms, followed by the onset of a single peripheral cue in either the right or left cue locations used in the Appearance task (7° right or left of fixation, 3° azimuth from the horizontal meridian) simultaneous with a tone (which signaled that the cue had appeared, in case its contrast was below threshold). Cue location was randomized between the two peripheral locations across trials. The cues varied randomly in Weber luminance contrast amongst 1%, 4%, 5%, 6%, 10%, 17.5%, 25%, and 50%. The cue contrast values used in this task encompassed a lower range than in the main experiment because we expected localization to asymptote at a low contrast. The cue remained onscreen for 50 ms as it would in the Appearance task. The participants were instructed to report the side of fixation on which the cue appeared by responding with a key designating the *side*, using "n" to answer for left and "m" for right. There were a total of 700 trials.

All observers met the 95% cue localization requirement to participate in subsequent phases of the study.

2.2.2.2. Stimulus localization. Each trial started with a fixation point for 750 ms, followed by a 100% contrast central cue for 50 ms. This task employed only a central cue at fixation to avoid allocating exogenous attention to either of the peripheral stimulus locations. Following an interstimulus interval (ISI) of 50 ms, a single Gabor stimulus was presented for 100 ms at one of the two stimulus locations. The stimulus localization task employed stimuli that were at the bottom three of our range (10%, 12.6%, and 17.8% Michelson contrast), which varied randomly. Stimulus orientation (tilt) was 5° right or left of vertical. Participants reported the location and orientation of the stimulus with a single key press. The keys "z" and "x" were used to indicate left and right tilt, respectively, for the left location, and the keys "n" and "m" were used to indicate left and right tilt, respectively, for the right location. There were a total of 336 trials. All observers met the 95% stimulus localization requirement to participate in subsequent phases of the study.

2.2.2.3. Appearance task training. A trial began with fixation on the central point for 750 ms, followed for 50 ms by a black 100% Weber contrast cue presented at fixation for 50 ms. The central cue location was used to familiarize observers with the timing and sequence of the Appearance task. There was an ISI of 50 ms, after which the stimuli were presented for 80 ms at the right and left stimulus positions. This task employed one stimulus at 10% Michelson contrast and a second at 28.2% contrast, the Standard contrast for the subsequent main appearance experiment, in order to make the comparative contrast judgment easy for training. The participants were asked to report the orientation of the higher contrast stimulus. They responded by pressing the key that indicated the *tilt* of the stimulus perceived to be higher in contrast. The keys "z" and "x" were used to indicate left and right tilt, respectively, for the left side of the fixation point, and the keys "n" and "m" were used to indicate left and right tilt, respectively, for the right side of the fixation point. A tone provided feedback for correctly choosing the higher contrast stimulus. Observers performed 80 trials, and all met the acceptance criterion of 95% correct performance.

2.2.2.4. Main experiment: appearance task with pre-cue. This task (Fig. 1) addressed the central issue of how the saliency of the visual cue affects the attentional effect by manipulating the cue contrast. Each trial began with 750 ms of fixation, followed randomly by a central cue at fixation or a peripheral cue above one of the stimulus locations. Cue contrast varied randomly amongst 6%, 9%, 12%, 25%, 50%, 75%, and 100%.

The cue was onscreen for 50 ms, followed by an ISI of 50 ms, which was then followed by the onset of the stimuli. In each trial, one stimulus (the Standard) was set at 28.2% contrast and the other stimulus (the Test) randomly varied amongst the following Michelson contrast values: 10%, 12.6%, 17.8%, 22.4%, 28.2%, 35.5%, 44.7%, 56.2%, and 79.4%, randomly tilted to the right or left of vertical. The stimuli remained onscreen for 80 ms, after which observers responded with a single key press. Time for response was not limited. The instruction and response procedure were the same as described above for the appearance training task. Participants performed six sessions of 1332 trials each, totaling 7992 trials over the course of 1–2 weeks. Each session had equal numbers of trials for all the combinations of Test stimulus location, Test contrast, cue contrast, cue position, and Standard and Test orientation, which were randomized within each session. As in earlier studies using this paradigm (Anton-Erxleben et al., 2007; Carrasco et al., 2004, 2008; Fuller & Carrasco, 2006; Fuller et al., 2008; Gobell & Carrasco, 2005; Ling & Carrasco, 2007; Liu, Fuller, & Carrasco, 2006; Montagna & Carrasco, 2006; Turatto et al., 2007), the location of the peripheral cue was randomized independently of the locations of the Test and Standard stimuli. The cue was therefore uninformative with regard to the location of the higher contrast stimulus on which observers were to report, being equally likely to appear near the higher or lower contrast stimulus. Sessions were subdi-

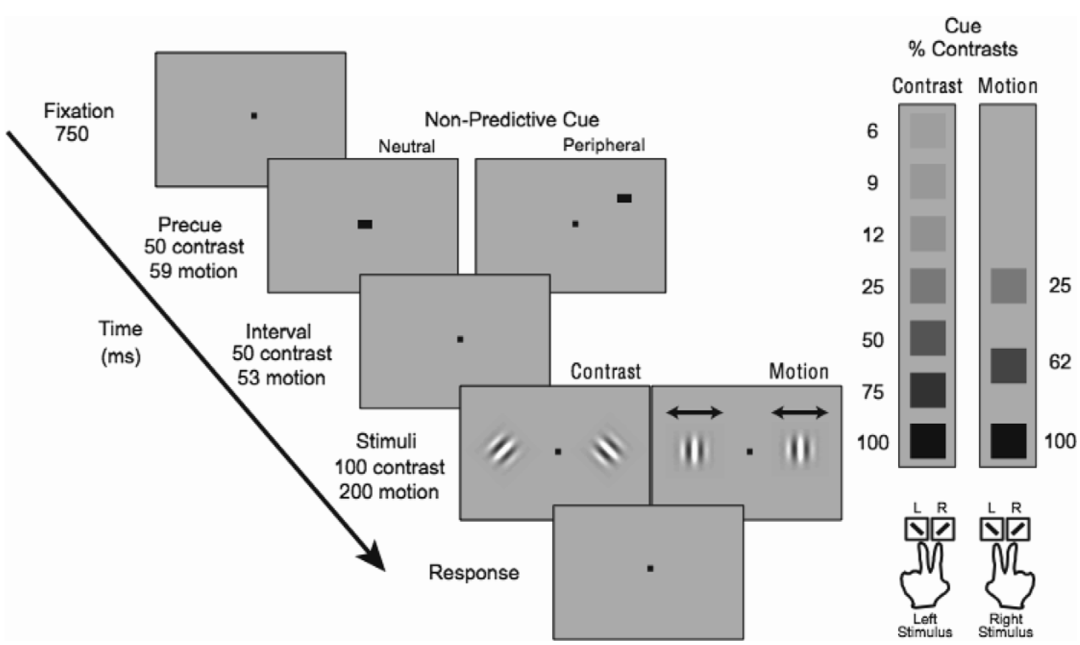

Fig. 1. Trial sequences for Experiments 1 and 2, Phase 2, pre-cue appearance task. Observers maintain fixation on the central dot throughout the experiments. After 750 ms, a brief cue is presented at fixation or peripherally above one of the two stimulus locations. In Experiment 1, two contrast stimuli are presented, after which observers report the orientation of the higher contrast stimulus. In Experiment 2, both stimuli have 60% contrast, but the gratings inside the Gabor envelopes move to the left or right at varying speeds. Observers report the direction of the faster moving stimulus. Cue contrast varies randomly amongst the contrast values for each experiment shown in the panels at right in the figure.

vided into 10 blocks, providing an opportunity for observers to take a brief rest break.

2.2.2.5. Control experiment: appearance task with post-cue. The control experiment session (Fig. 2) was administered on the day following the completion of the main experiment. The purpose of this session was to rule out cue bias as an explanation for cue effects in the main experiment. The task was the same as the main experiment, but the critical difference is that the cue was presented *after* the stimuli, precluding any attentional effect of the cue (Anton-Erxleben et al., 2007; Carrasco et al., 2008; Gobell & Carrasco, 2005; Turatto et al., 2007). There were a total of 1296 trials. The post-cue was set at 100% Weber contrast, for comparison to the 100% pre-cue in the main experiment. All other specifications aside from the order of cue and stimuli were identical to the main experiment.

2.2.3. Results

2.2.3.1. Cue localization. The results of the cue localization task for each participant were fitted using two-parameter Weibull psychometric functions, with the probability of reporting the correct side as the dependent variable, and the log-contrast of the cue as the independent variable. Fig. 3A shows the pooled data for all 6 observers, demonstrating that the cue was nearly perfectly localizable at ~10% cue contrast. The corresponding panels in Fig. 4 illustrate the individual variations, with perfect localization ranging from ~5% to ~12%.

2.2.3.2. Main experiment: appearance task with pre-cue. The trials for each observer were grouped by cue contrast, and fitted by the three cue conditions: the cue appeared near the Test stimulus in the Test-cued condition, near the Standard stimulus in the Standard-cued condition, and at fixation in the Neutral cue condition. Psychometric functions (Weibull) of the probability of reporting the Test stimulus as higher in contrast compared to the Standard stimulus, as a function of the log-contrast of the Test stimulus, were fit to each of the three cue conditions, psignifit version 2.5.6 (see http://bootstrap-software.org/psignifit/), a software package which implements the maximum-likelihood method described by (Wichmann & Hill, 2001). The point of subjective equality (PSE) was calculated for each fit by inverting the Weibull function to estimate the Test stimulus contrast at which participants would choose the Test stimulus at chance probability (0.5).

The signature effects of exogenous attention on stimulus appearance are shifts of the psychometric functions for the Test-cued and Standard-cued conditions in opposite directions away from the function for the Neutral cue condition. In prior studies using the same paradigm for apparent contrast judgments (Carrasco et al., 2004, 2008; Fuller et al., 2008; Hsieh et al., 2005; Ling & Carrasco, 2007), the function for the Test-cued condition shifted toward lower Test stimulus contrasts, and the function for the Standard-cued condition shifted toward higher Test contrast. Whereas in the Neutral cue condition the PSE occurred when the Test stimulus had equal physical contrast as the Standard stimulus, in the Test-cued and Standard-cued conditions the PSEs occur at unequal physical contrasts. When exogenous attention was deployed to the location of the Test stimulus, it was lower in contrast than the Standard but still judged by observers to be equivalent in apparent contrast. Conversely, when the Standard stimulus was cued, the Test stimulus required higher physical contrast to be judged equivalent. This pattern indicated that exogenous attention deployed to the location of a stimulus increased its apparent contrast.

There were a total of 21 psychometric function fits performed per observer for *Phase 2* (3 cue conditions × 7 cue contrast values). A within-subjects analysis of covariance (ANCOVA) was run on the observers' PSEs for the three cue conditions, with the log-contrast of the cue as a covariate and observer (nominal) as a between-subject factor. The statistics of interest were (a) the main effect of cue condition, which would indicate whether the PSEs differ for Test, Neutral, and Standard cues, (b) the interaction of cue log-contrast and cue condition which if significant would indicate presence of a cueing effect that varies with cue contrast, and (c) the covariate

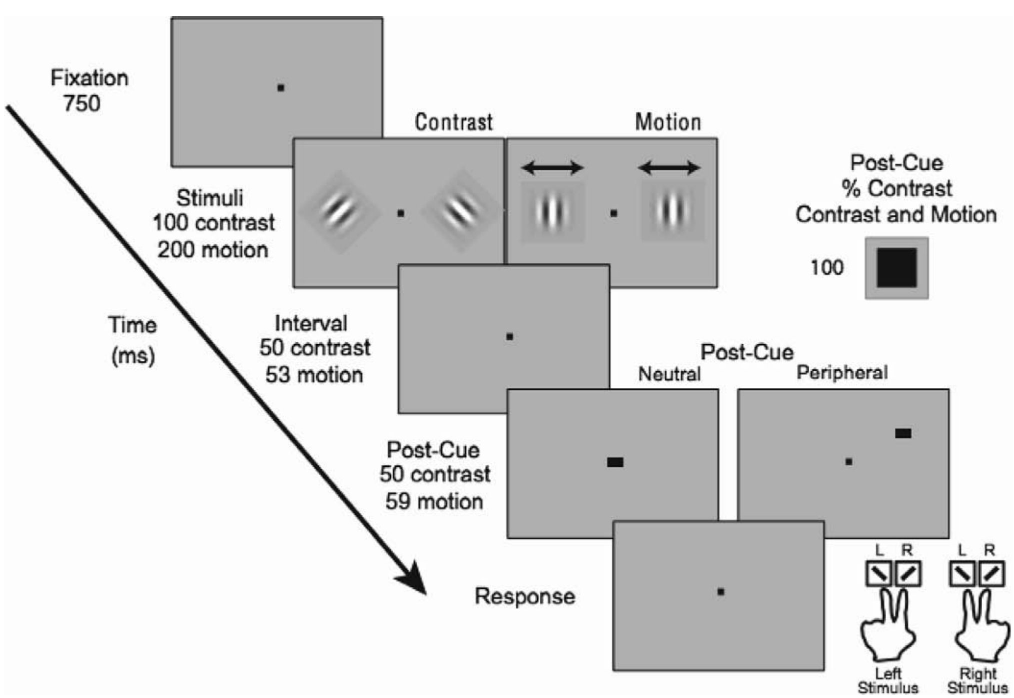

Fig. 2. Trial sequences for Experiments 1 and 2, Phase 3, post-cue appearance task. Both have the same timing parameters as in the pre-cue appearance task, but the presentation order of stimuli and cues is reversed as a control for cue bias. Cue contrast is 100% for comparison with the 100% contrast pre-cue results. If there is no difference in PSEs by cue condition (Test, Neutral, and Standard) with the post-cue, then cue bias cannot explain any differences present in the pre-cue results.

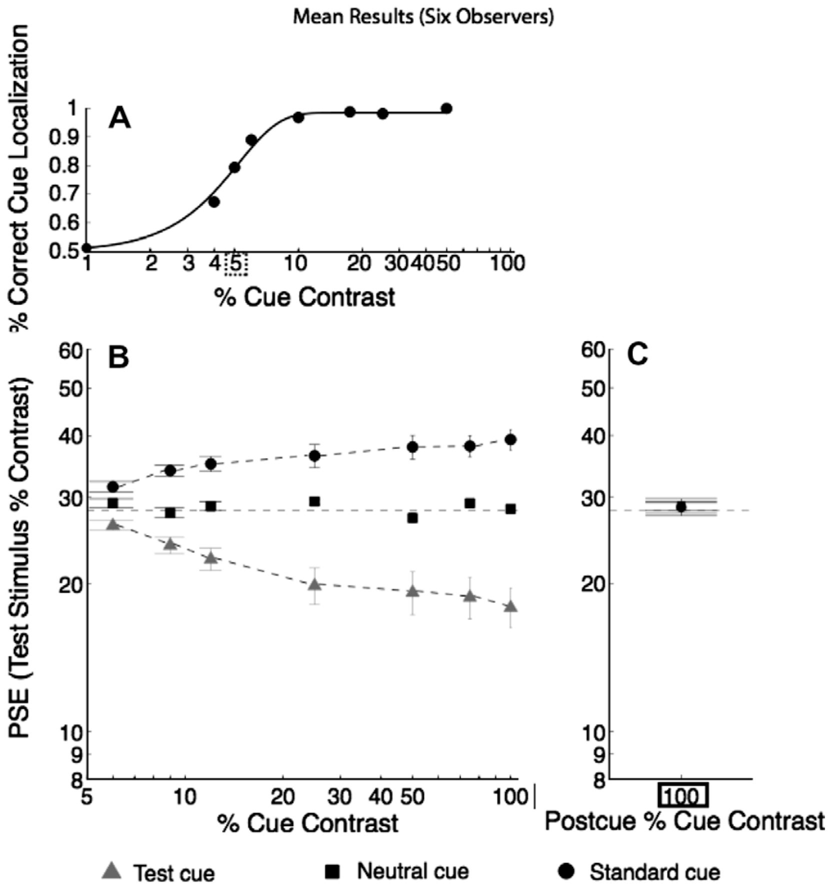

Fig. 3. Mean results for all observers in Experiment 1 with contrast stimuli. Panel A: cue localization asymptotes at ~12% cue contrast. Panel B: PSEs by cue condition (Test stimulus cued = light gray triangles, Neutral cue = black squares, Standard stimulus cued = medium gray dots) on the vertical axis by cue% contrast on the horizontal axis. At cue contrasts below localization asymptote, the attentional effect increases, with cue visibility likely a factor (see Table 1 for statistics). The attentional effect continues to increase for cue contrasts >12%, after cue localization has peaked, indicating a positive relationship between cue salience and the magnitude of the attentional modulation of apparent contrast. Panel C: results for the 100% contrast post-cue show no effect of attention, ruling out cue bias as an explanation for the pre-cue results in Panel B. All error bars are 1 SE of the mean.

parameter estimates for the three cue conditions (β_{Test}, $\beta_{\mathrm{Standard}}$, and β_{Neutral}). The covariate parameters for log-cue contrast were expected to be zero for the Neutral cue condition, i.e. the PSEs in this condition were expected to occur approximately at a Test contrast physically equal to the Standard contrast and there would be no change with the contrast of the Neutral cue. Prior studies of apparent contrast (Carrasco et al., 2004, 2008; Fuller et al., 2008; Hsieh et al., 2005; Ling & Carrasco, 2007) found that the PSEs for the Test-cued and Standard-cued condition shifted toward higher Test contrast (a positive shift). If the magnitude of the attentional effect increased with cue contrast, then the cue contrast covariate parameters would be expected to be non-zero and have corresponding signs (negative for the Test-cued condition, positive for the Standard-cued condition).

A summary of the statistics appears in Table 1, and the pooled results for the six observers appear in Fig. 3. The first column of Table 1 summarizes the results across all cue log-contrasts. The significant main effect of cue agrees with prior studies using this paradigm with contrast (Carrasco et al., 2004, 2008; Fuller et al., 2008; Hsieh et al., 2005; Ling & Carrasco, 2007): the PSE shifts toward *lower* Test stimulus contrast when the Test is cued, toward *higher* Test stimulus contrast when the standard is cued, and in the Neutral cue condition the PSE is at a Test contrast that is approximately equal to the Standard contrast. Moreover, the cue condition $\times$ cue log-contrast interaction is also significant, indicating, as shown in Fig. 3B, that increasing cue contrast increases the magnitudes of the PSE shifts for the Test and Standard cue conditions, but has no effect on the PSE for the Neutral cue condition.

By design, our cue contrast range included values that were below our observers' threshold of perfect cue localization. On some trials at these low cue contrasts, the cue might not have been clearly visible. Although there is evidence that in speeded detection tasks attention can be automatically deployed in response to imperfectly visible or subliminal cues (McCormick, 1997; Mulckhuyse et al., 2007), it is also possible that poor cue visibility could explain modulation of the attention effects below the localization threshold. The hypothesis that cue salience modulates the effect of exogenous attention would be better supported by evidence for cue contrasts above that threshold. The ANCOVA model assumes a linear effect of the covariate. Therefore, in the overall analysis described above, the β_{Test} and $\beta_{\mathrm{Standard}}$ values might be significantly different from zero even if cue contrast was a factor only low contrasts, i.e. when the cue was not perfectly localizable, but not for higher, suprathreshold cue contrasts. To test for this possibility, we divided the data into two subsets according to cue contrast: observer PSEs for cue contrasts <12%, the range for which observers had shown less than perfect cue localization ("pre-asymptotic"), and $\geqslant$12%, values at which localization had asymptoted for all observers ("post-asymptotic"). These results are summarized in columns 2 and 3 of Table 1. For both pre-asymptotic and post-asymptotic cue contrasts, the β_{Neutral} coefficients did not differ significantly from zero, as would be expected when

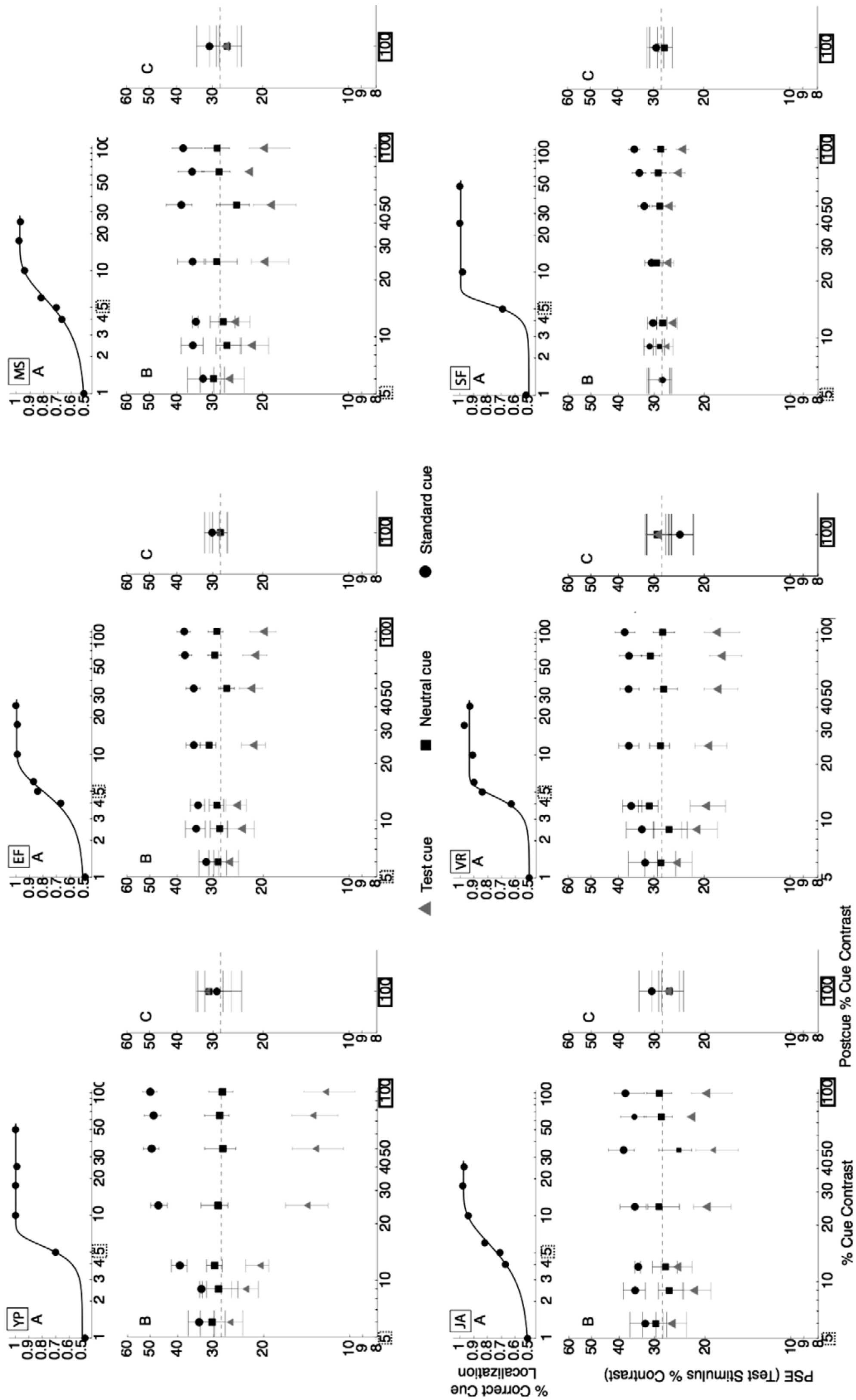

Fig. 4. Individual observer results for Experiment 1. Panels A–C are configured the same as in Fig. 2. All observers show increasing attentional effects with increasing cue contrast, even after they are able perfectly to localize the cue. The magnitude of the effect with 100% contrast pre-cues (Panel A) varies by observer, as does the rate of change with lower pre-cue contrasts. Reversing the order of stimuli and cue presentation (post-cue, Panel C) eliminates the attentional effect for all observers.

attention is not preferentially allocated to either stimulus location. With the pre-asymptotic cue contrasts, the β_{Test} coefficient was significant ($p < .05$), and the β_{Standard} coefficient is marginally significant ($p = .07$). More importantly, column 3 of Table 1 shows that for post-asymptotic cue contrasts, the main effect of cue condition and the cue condition $\times$ cue log-contrast interaction were

Table 1
Statistical results for Experiment 1: contrast.

	Full cue contrast range {6–100%}	Pre-localization cue contrasts {6–12%}	Post-localization cue contrasts {12–100%}	Post-Cue {100%}
Cue	$F(2, 70) = 226$, $p < .001$, $h^2 = .87$	$F(2, 22) = 12.2$, $p < .001$, $h^2 = .87$	$F(2, 46) = 33.6$, $p < .001$, $h^2 = .94$	$F(2, 20) < 1$
Cue * log_contrast	$F(2, 70) = 34$, $p < .001$, $h^2 = .5$	$F(2, 22) = 5.6$, $p < .01$, $h^2 = .87$	$F(2, 46) = 18.3$, $p < .001$, $h^2 = .44$	n/a
β_{Test}	$\beta_{\mathrm{Test}} = -.12$, $t(5) = 28.9$ $p < .001$	$\beta_{\mathrm{Test}} = -.18$, $t(5) = 9.3$ $p < .001$	$\beta_{\mathrm{Test}} = -.10$, $t(5) = 4.6$ $p < .001$	n/a
β_{Neutral}	$\beta_{\mathrm{Neutral}} = -.002$, $t(5) = .2$ $p > .8$	$\beta_{\mathrm{Neutral}} = -.013$, $t(5) = .24$ $p > .8$	$\beta_{\mathrm{Neutral}} = -.007$, $t(5) = .69$ $p > .5$	n/a
$\beta_{\mathrm{Standard}}$	$\beta_{\mathrm{Standard}} = .06$, $t(5) = 5.9$ $p < .001$	$\beta_{\mathrm{Standard}} = .11$, $t(5) = .74$ $p = .07$	$\beta_{\mathrm{Standard}} = .05$, $t(5) = 5.9$ $p < .001$	n/a

significant. Moreover, β_{Test} and $\beta_{\mathrm{Standard}}$ were significantly different from zero, again with the expected signs as explained above: test cue condition PSEs decreased with increasing cue log-contrast, whereas Standard cue condition PSEs increased with cue log-contrast. Because this analysis was confined to cue log-contrasts that were perfectly localizable by our observers, we can rule out the sub-threshold cue visibility on some proportion of trials as an explanation of the results.

2.2.3.3. Control experiment: appearance task with post-cue. Another possible explanation for the modulated attentional effect observed in the main experiment would be cue bias or some perceptual interaction between the cue and stimulus that scaled with cue contrast. Presenting the cue after the stimuli served as a control for this possibility.

The results from the post-cue session were fitted by observer using the same methodology as in *the main appearance task*. A one-way, within-subjects ANOVA was performed on the PSEs of the six observers by cue condition to determine if there was an effect due to the cue, which, because of the reversed order of stimuli and cue presentation, would indicate cue bias.

There was no significant effect of the 100% contrast post-cue, $F(2, 10) < 1$ (Table 1, column 4), and none of the three mean PSEs (Test, Neutral, and Standard cue) differed significantly from the 28.2% physical contrast of Standard stimulus (Fig. 3C). This indicates that neither cue bias nor sensory interaction can account for the cueing effect and the scaling of the effect with cue contrast. Cue bias and sensory interaction would not have been affected by reversing the presentation order of cues and stimuli, whereas an attentional effect can only occur when the cues precede the stimuli.

2.3. Experiment 2: speed

In Experiment 1, cue salience was modulated along the same visual dimension as our stimuli and task were defined: contrast. The phenomenon of contingent capture, in which the automatic orienting effects of an onset distracter or cue can be overridden if the stimulus feature relevant to a task is different from the defining feature of the cue (e.g. Folk et al., 1992), raises the possibility that the scaling with cue contrast observed in Experiment 1 may have depended on the match between our dimension for cue salience (contrast) and the stimulus dimension for the task (also contrast). Whereas changes in appearance with exogenous attention have been reported using luminance cues and stimuli defined on other dimensions (size: Anton-Erxleben et al., 2007; color saturation: Fuller & Carrasco, 2006; spatial resolution: Gobell & Carrasco, 2005; flicker rate: Montagna & Carrasco, 2006; motion (Liu et al., 2006; Turatto et al., 2007), these studies all used single-value, high contrast cues. To test whether the scaling in the results of Experiment 1 were somehow due the cue modulation and the task judgment involving the same visual dimension (contrast), in Experiment 2 we used the appearance procedure in conjunction with a motion speed task, following specifications of Turatto et al. (2007). The stimuli all had the same physical contrast (60%), and the task was to "report the direction of the faster moving stimulus", thus placing the judgment and the relevant stimulus feature on a different dimension than cue contrast.

2.3.1. Stimuli and cues

The stimuli were Gabor patches (1 cpd spatial frequency; $3° \times 3°$, 60% contrast, with the width of the Gaussian envelope at half height $\sim 0.8°$) located at 4° eccentricity left or right of the center fixation point. The sinusoidal grating within each Gabor moved horizontally at one of 7 speeds: 1.88, 3.13, 3.75, 4.29, 5.02, 6.82, or 12 deg./s (all speeds except the last are the same as in Turatto et al. (2007); we reduced their highest speed, 15 deg./s, because it was far above the dynamic range for their observers).

Cues were 0.6° dots at fixation (Neutral condition) or centered at 2° above the center of the stimuli. We employed 6 cue contrasts in Phase 1 (cue localization, see Procedure): 4%, 6%, 8%, 10%, 12%, and 25%; three contrasts in Phase 2 (appearance task, see Procedure): 25%, 66%, and 100%, and 1 contrast (100%) in Phase 3.

2.3.2. Specific procedures

2.3.2.1. Peripheral cue localization. Observers performed a brief cue localization experiment similar to Experiment 1, Phase 1, consisting of 600 trials. Each trial began with a tone concurrent with a single peripheral cue, which was presented for 50 ms at one of the peripheral locations used in the main experiment (4° left and right of fixation, 2° azimuth, cue size 0.6°). As in Experiment 1, *Phase 1*, the cue contrasts were lower than in the main experiment in order to measure the cue contrast at which observers began to localize the cue perfectly.

2.3.2.2. Appearance task training. Observers trained on the motion appearance task in a run of 80 trials, for which the speed comparison was fixed at a simple level (Standard stimulus 4.29 deg./s and Test stimulus 12 deg./s) and a double tone at the end of each trial provided feedback for correctly choosing the faster moving Gabor. All observers met the acceptance criterion of 95% correct performance.

2.3.2.3. Main experiment: appearance task with pre-cue. The trial schematic is shown in Fig. 1. The timing parameters replicate those used by Turatto et al. (2007). On each trial, a cue was presented for 59 ms, followed by an ISI of 53, then two Gabor stimuli with horizontally moving gratings appeared for 200 ms. The grating speed for the Standard stimulus was 4.29 deg./s, whereas the Test speed varied randomly among the full range of speeds, including the Standard. Observers reported "the direction of the grating that is moving faster." The "z" and "x" keys indicated the faster stimulus was in the left stimulus location, moving leftward or rightward, respectively, and the "n" and "m" keys represented the right stimulus location with corresponding motion directions. Cue contrast, cue location, Test and Standard stimulus locations, and Test and Standard motion directions (right or left), were independently randomized. As in Experiment 1, the location of the cue was uninformative regarding the location of the faster moving stimulus. Observers completed three sessions of the experiment, 1008 trials per session, over the course of 1 week.

2.3.2.4. Control experiment: appearance task with post-cue. In the control task, we reversed the presentation order of stimuli and cue so that the post-cue appeared after the stimuli, as in Experiment 1. The task remained the same as in Phase 2. A schematic and timing parameters appear in Fig. 3.

2.3.3. Results

2.3.3.1. Peripheral cue localization. Fitting procedures were the same as for Peripheral Cue Localization in Experiment 1. Pooled results are shown in Fig. 5A, and individual observer results in the A panels of Fig. 6. The mean cue contrast at which observers reached asymptotic localization performance was $\sim 6\%$, with a range from 4 to 7, lower than in Experiment 1, *Phase 1*, due to the greater size and reduced eccentricity of the cues.

2.3.3.2. Main experiment: appearance task with pre-cue. The data for the motion appearance task were fitted and analyzed in the same way as the contrast appearance data (see Experiment 1, Results), using a within subjects ANCOVA on the individual observer PSE estimates for the three cue conditions (Test, Neutral, and Standard) with cue log-contrast as a covariate and observer as a between subjects factor.

Pooled results are shown in Fig. 5B, and individual observer results in the B panels of Fig. 6. Statistical results are shown in Table 2. The directions of the PSE shifts matched those reported by Turatto et al. (2007): for the Test-cued condition, the PSE occurred when the Test stimulus moved at a slower physical speed than the Standard stimulus, and for the Standard-cued condition at a Test stimulus speed that was higher than the Standard stimulus, suggesting that exogenous attention increases the apparent speed of a moving Gabor grating. Similar to Experiment 1 in the present study, there were significant cue condition and cue condition X cue log-contrast effects. The cue log-contrast coefficients β_{Test} and β_{Standard} were significant and had the expected negative and positive signs, respectively, whereas β_{Neutral} did not differ from zero. As in Experiment 1, the attentional effect modulated with cue-contrast, at levels of cue contrast well above the perfect cue localization threshold.

2.3.3.3. Control experiment: appearance task with post-cue. As in Experiment 1, when the 100% contrast cue was presented after the stimuli, there was no effect of the post-cue on apparent speed (see pooled results in Fig. 5C, and individual observer results in the C panels of Fig. 6; $F(2,8) < 1$). This finding rules out perceptual interaction and cue bias as explanations for the effect of the peripheral cues on apparent speed, and for the scaling of the effect with cue contrast. Moreover, because cue salience was varied on a visual dimension that differed from the stimulus feature used to perform the task, this experiment shows that the scaling does not depend on concurrence between the relevant dimensions of the cue and the stimuli.

3. General discussion

A reader of the literature could easily infer from exogenous attention's automatic nature that the cueing mechanism might be inflexible, i.e. that above some cueing threshold, the size of the attentional effect is fixed. The present study, however, has

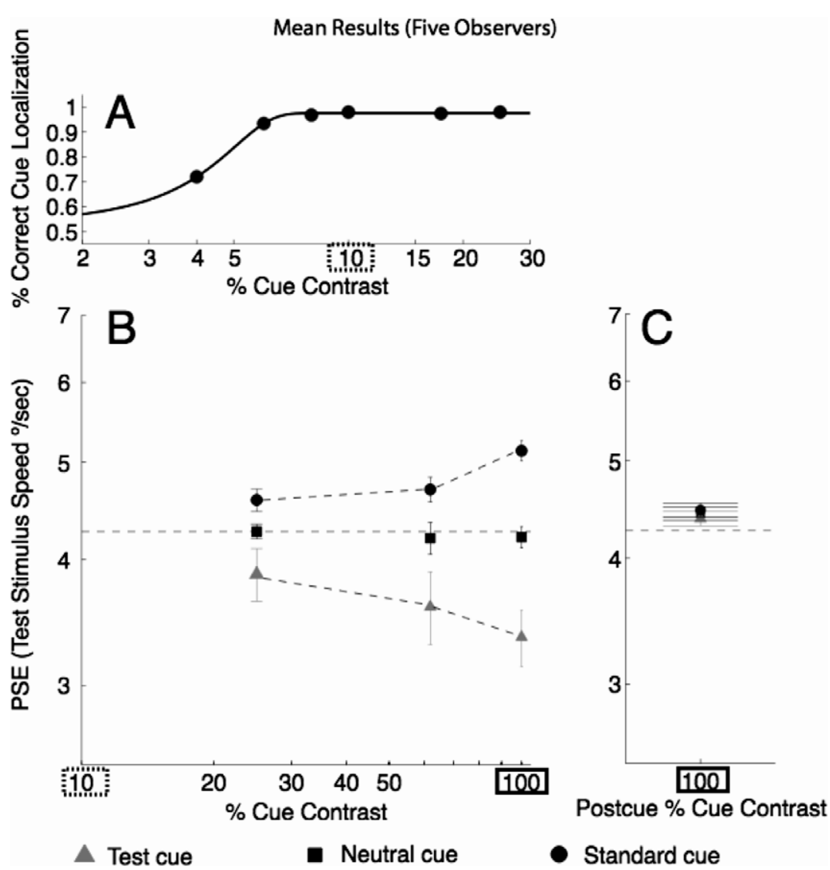

Fig. 5. Mean results for all observers in Experiment 2 with motion stimuli. Panel A: cue localization asymptotes at ~6% cue contrast. Panel B: PSEs by cue condition (Test stimulus cued = light gray triangles, Neutral cue = black squares, Standard stimulus cued = medium gray dots) on the vertical axis by cue % contrast on the horizontal axis. All pre-cue contrasts are above the asymptote for cue localization, and the attention effect on apparent motion increases with cue contrast. Panel C: results for the 100% contrast post-cue show no effect of attention, ruling out cue bias as an explanation for the pre-cue results in Panel B. All error bars are 1 SE of the mean.

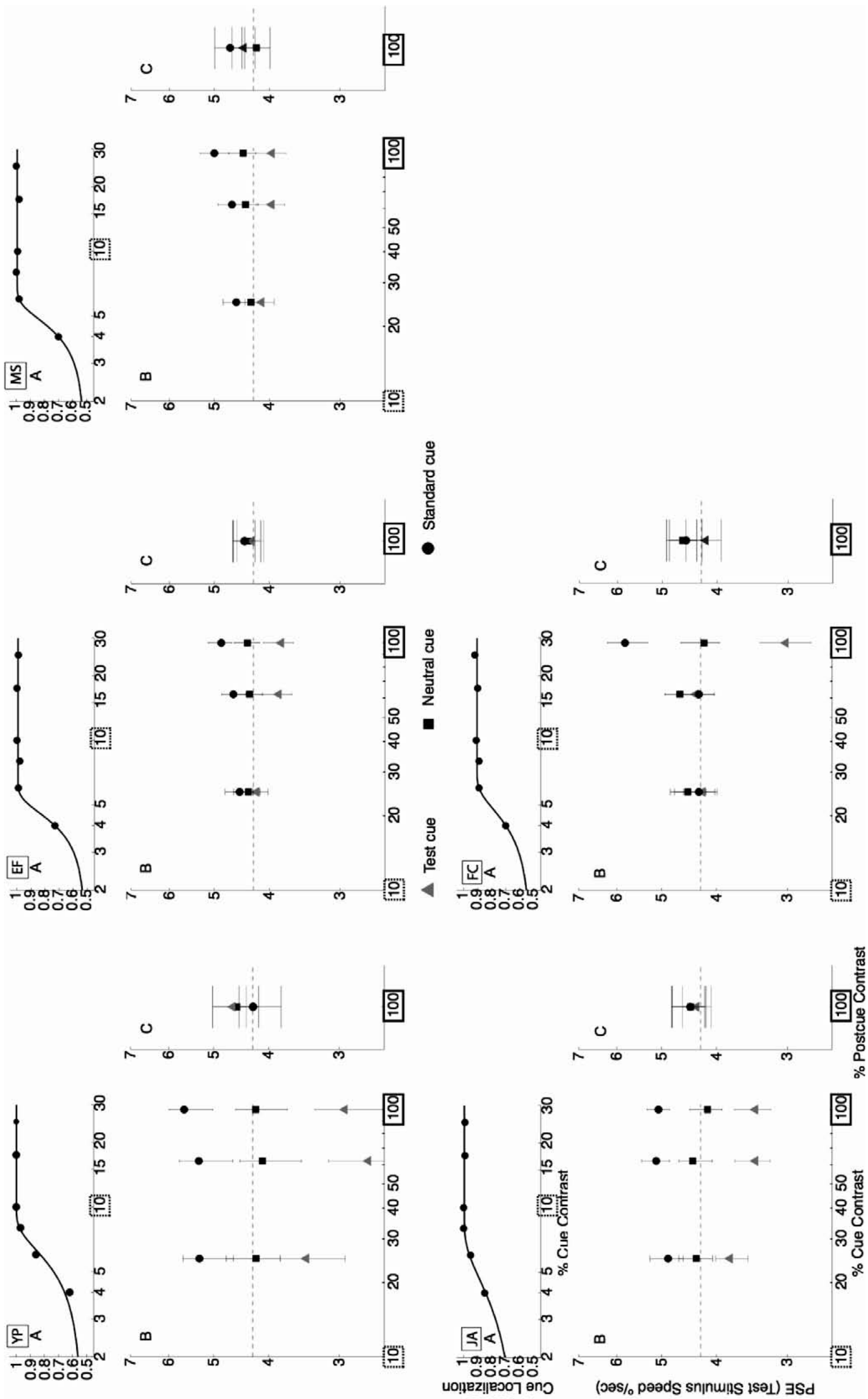

Fig. 6. Individual observer results for Experiment 2. Panels A–C are configured the same as in Fig. 5. All observers show increasing attentional effects with increasing cue contrast, at cue contrasts above the cue localization asymptote. The magnitude of the effect with 100% contrast pre-cues (Panel A) varies by observer, as does the rate of change with lower pre-cue contrasts. Reversing the order of stimuli and cue presentation (post-cue, Panel C) eliminates the attentional effect for all observers.

found that the magnitude of exogenous attention's effect on apparent contrast and apparent speed of motion is modulated by cue salience, with salience implemented here as cue contrast with the background. The magnitude of the attentional effect scaled across the full range of contrasts used. In Experiment 1, using luminance contrast cues and an orientation discrimination task with contrast

Table 2
Statistical results for Experiment 2: motion.

	Full cue contrast range {25–100%}	Post-Cue {100%}
Cue	$F(2, 18) = 56.5$ $p < .001$, $h^2 = .86$	$F(2, 8) < 1$
Cue*log_contrast	$F(2, 18) = 8.1$ $p < .005$, $h^2 = .48$	n/a
β_{Test}	$\beta_{Test} = -.10$ $t(4) = 2.85$ $p < .05$	n/a
$\beta_{Neutral}$	$\beta_{Neutral} = -.01$ $t(4) = .7$ $p > .5$	n/a
$\beta_{Standard}$	$\beta_{Standard} = .07$ $t(4) = 2.6$ $p < .05$	n/a

stimuli, we showed significant effects of cue contrast, both below and above the localization threshold and attentional scaling at suprathreshold cue contrasts. In Experiment 2, using the same luminance contrast cues, we verified the attentional scaling at suprathreshold cue contrasts, with motion stimuli and a motion discrimination task. This finding rules out an explanation that the scaling in Experiment 1 resulted from perceptual interaction between the contrasts of the cues and of the stimuli, or that it was contingent upon correspondence between the cue feature and the stimulus and task feature.

The ability to localize the cue is unnecessary for engaging exogenous attention. This is consistent with prior studies, using subliminal cues (McCormick, 1997; Mulckhuyse et al., 2007). If awareness of the cue is not required, it logically follows that conscious localization may not be required either. Mulckhuyse et al. (2007) proposed that the engagement signal for exogenous attention in their study may have originated in the superior colliculus, engaging attention via its efferents to parietal cortex. Both McCormick (1997) and Mulckhuyse et al. (2007) have suggested that the mechanism engaging exogenous attention in their experiments may also account for the ability of visual-cortex damaged blindsight patients to report the location of stimuli at rates above chance.

3.1. Attentional scaling

The evidence for automaticity (e.g., Giordano et al., 2009; Liu, Pestilli, & Carrasco, 2005; Montagna et al., 2009; Müller & Rabbitt, 1989; Pestilli & Carrasco, 2005; Pestilli et al., 2007; Theeuwes, 1991, 1992; Theeuwes & Burger, 1998; Theeuwes & Godijn, 2002; Yantis & Jonides, 1984) and the effectiveness of subliminal cues (McCormick, 1997; Mulckhuyse et al., 2007) engaging exogenous attention suggest an exogenous cueing mechanism that is fairly inflexible. The findings of this study, however, show that exogenous attention does not behave like an absolute binary on–off mechanism, which always switches on beyond a given specific point, be it subthreshold, threshold or suprathreshold. How could the scaling of the exogenous attention effect reported here arise? There are two interesting questions here: (1) what is the nature of the aggregate (across trials) attentional scaling that we observed in the present study, and (2) how might these results relate to prior studies showing attentional deployment following subliminal cues?

Regarding the nature of the scaling, the two simplest explanations depend on different characterizations of the cueing mechanism. If the deployment of exogenous attention is an "all-or-nothing/none" phenomenon, like a binary "on-off" switch, then the scaling in our experiments could result from probabilistic engagement in response to cues of different contrasts. Attentional deployment on a larger proportion of trials at a given cue contrast would lead to a greater aggregate attentional magnitude measured across trials. Alternatively, the same pattern of results could arise if the cueing mechanism operated like a "dimmer" switch, with a continuous range of "on" settings above some minimum threshold. In this model, attention could be deployed on every trial, with the magnitude of the attentional modulation increasing with the strength of the visual input from the cue. Unfortunately, these explanations cannot be differentiated on the basis of the present study. Although given the automaticity of exogenous attention, it would be an unexpected degree of flexibility if the cueing mechanism operated like "dimmer", we speculate that it could be ecologically advantageous. In a survival context, probabilistic engagement of exogenous attention as a function of cue salience carries a risk of failing to grant priority processing to the location of a sudden onset or change that represents a predator or prey, a "Type II error" with potentially serious consequences in any particular occurrence. The corresponding "Type I error," fully engaging attention to a location with no behavioral significance, can be similarly disadvantageous. Given that attention de-prioritizes visual processing at unattended locations (Montagna et al., 2009; Pestilli & Carrasco, 2005; Pestilli et al., 2007), this error could cause more relevant detail in the visual field to be overlooked, with similar consequences. A graded attentional response, on the other hand, enhancing processing at the attended location and decrementing processing at other locations according to cue salience could be thought of as scaling "appropriately" to the potential behavioral relevance of the cue.

In terms of physiological mechanisms that may link scaling with suprathreshold cues to prior results with subliminal cues, consider the proposal of McCormick (1997) and Mulckhuyse et al. (2007) that signals from the superior colliculus directly to parietal cortex can be sufficient to engage attention, even though the spatial information in the signal as it passes through visual cortex is too weak at higher areas to reach awareness. One possibility is that progressively increasing the contrast of the cues in the present study may have increased the strength of the direct signal from the superior colliculus, leading either to an increased probability of attentional deployment, or increasing the magnitude of the attentional modulation. In this sense, the signals carrying spatial information about the cue through visual cortex may be important for awareness and localization of the cue, but surprisingly, irrelevant for engaging exogenous attention. Another possibility is that the signal carrying information about the cue through visual cortex may also matter, and that the combined strength of the signals reaching parietal cortex via the superior colliculus and visual cortex bear on the probability or strength of attentional deployment.

3.2. Cue bias

A cue bias explanation does not support the pattern of results that we report here. We propose that if cue bias underlaid the scaling with cue contrast in our results, then the pattern of attentional effects should resemble the cue localization functions (Figs. 3A and 5A) for the two experiments. The magnitude of the attention effect would seem to scale up to the threshold cue contrast at which the cue is perfectly localized – once cue contrast reached this asymptotic level, the magnitude of the cueing effect would stabilize. Under this explanation, observers would choose the Test stimulus more frequently when it is cued, and less frequently when the Standard is cued. The scaling of this effect only at low cue contrasts would result from observers' inability to correctly localize the cue on some of these trials. When the cue is not localized, observers would make their selection of which stimulus to report on free of bias from a peripheral cue. Conversely, when the cue is localized, the bias would be present. As the proportion of trials for which the cue could be localized increases, the cueing effect would increase, up to the cue contrast at which cue localization stabilizes.

Our results show a continued increase in the magnitude of the cueing effect with cue contrasts above the point of perfect localization. This result adds further support to the argument that the cueing effect on appearance using this paradigm, in the present study and others, is indeed due to exogenous spatial attention and not cue bias. The evidence in favor of an attentional change in appearance, and against cue bias, includes the following (see Carrasco et al., in press, for a detailed discussion):

1. In the present study, the cueing effect occurs when the cue precedes the stimuli, a condition necessary for exogenous attention to influence stimulus perception, but not when the cue is presented after the stimuli (see also Anton-Erxleben et al., 2007; Carrasco et al., 2008; Gobell & Carrasco, 2005; Turatto et al., 2007).
2. Pre-cueing has no effect on observers' responses when they make a subjective comparison on the basis of stimulus hue (Fuller & Carrasco, 2006), whereas it does affect judgments of contrast (Carrasco et al., 2004, 2008; Fuller et al., 2008; Hsieh et al., 2005; Ling & Carrasco, 2007), flicker rate (Montagna & Carrasco, 2006), motion coherence (Liu et al., 2006), speed of moving stimuli (Turatto et al., 2007), size of moving stimuli (Anton-Erxleben et al., 2007), and spatial frequency (Gobell & Carrasco, 2005). Cue bias should depend only upon observers' ability to see the cue (which in Fuller & Carrasco, 2006 was 100 cd/m^2 on a 3 cd/m^2 background, hence highly visible), not the visual domain in which the task judgment is grounded.
3. The pre-cue alters appearance responses at SOAs ~120 ms, but not at SOAs ~500 ms (Carrasco et al., 2004; Fuller et al., 2008; Hsieh et al., 2005; Liu et al., 2006; Turatto et al., 2007). Exogenous attention has a limited time course, peaking at ~120 ms and decaying well before 500 ms (Cheal & Lyon, 1991; Nakayama & Mackeben, 1989; Remington, Johnston, & Yantis, 1992), whereas cue bias should not be dependent on SOA.
4. The effect of the cue varies at different locations in the visual field – it is greater on the lower vertical meridian than on the upper vertical meridian (Fuller et al., 2008). Cue bias predicts the opposite: with the suprathreshold cues used in Fuller et al. (2008), observers should have been more biased by the cue on the upper vertical meridian, where contrast sensitivity, and hence visibility of the contrast stimuli, is lower. It is important to note, however, that the reported asymmetry was present even with high contrast, suprathreshold stimuli (Fuller et al., 2008), whereas cue bias is more likely to occur with low contrast, low visibility stimuli (Carrasco et al., 2008).
5. Several of the appearance studies have reported difference in discrimination performance for cued and uncued stimuli when the performance component of the task was sufficiently difficult to allow room for performance improvements and impairments, i.e., performance was not at ceiling (Anton-Erxleben et al., 2007; Carrasco et al., 2004; Fuller & Carrasco, 2006; Fuller et al., 2008; Ling & Carrasco, 2007; Liu et al., 2006). These studies showed that the pre-cue engendered the signature effect of exogenous attention. Moreover, cue bias predicts no such changes in discrimination performance.
6. BOLD responses in visual cortex are increased by pre-cueing, but not by post-cueing (Liu, Pestilli & Carrasco, 2005). There is no satisfactory cue bias explanation for this finding, particularly given that the cues and stimuli were presented on opposite sides of the horizontal meridian, separating their cortical representations in early cortical areas so that the BOLD signals from cues and stimuli were not confounded.

3.3. Sensory interaction

Sensory interaction between the cue and the stimuli can also be eliminated as an explanation for both the cueing effect and its scaling with cue contrast. This explanation rests on the fact that visual signals are integrated over a time, i.e. that the percepts of a cue and a stimulus presented within this window in close spatial proximity might "contaminate" one another. Such an interaction should be present whether the cue is presented before or after the stimuli, but the present study and others show that this is not the case (Anton-Erxleben et al., 2007; Carrasco et al., 2008; Gobell & Carrasco, 2005; Turatto et al., 2007). Moreover, it follows directly that the polarity of the cue contrast should matter if the cueing effect is due to sensory interaction: Schneider (2006) predicted that a black cue (as used in the present study) should *decrease* subjective contrast of the cued stimulus, whereas a white cue should *increase* subjective contrast. Ling and Carrasco (2007) and Carrasco et al. (2008) subsequently tested black and white cues within the same paradigm using Gabor contrast stimuli, finding that in both cases they increased apparent contrast.

A related question is whether modulating cue salience in the contrast dimension for contrast-based stimuli and task might be responsible for our graded results. We showed the same pattern post-asymptotic cue contrasts for a motion task, following Turatto et al. (2007). Whereas Experiment 2 stimuli were also Gabors, they were high contrast (60%), and more importantly the task dimension of movement speed was orthogonal to the contrast dimension along which cue salience was varied.

4. Conclusions

We tested the effect of varying the contrast, i.e. salience, of an exogenous cue on the magnitude of the attentional effect on apparent contrast (Carrasco et al., 2004, 2008; Fuller et al., 2008; Ling & Carrasco, 2007) and apparent speed of motion (Turatto et al., 2007). Despite the automaticity of exogenous attention (e.g., Giordano et al., 2009; Liu et al., 2005; Montagna et al., 2009; Müller & Rabbitt, 1989; Pestilli & Carrasco, 2005; Pestilli et al., 2007; Theeuwes, 1991, 1992; Theeuwes & Burger, 1998; Theeuwes & Godijn, 2002; Yantis & Jonides, 1984), we have found a surprising degree of gradation in the attentional response: its magnitude varies with cue contrast, even at contrasts that exceed the threshold for perfect localization of the cue. This variable response cannot be attributed to inconsistent or low visibility of the cue, or to cue salience being varied on the same visual dimension as the task as evidenced by the same results for motion stimuli as for contrast stimuli.

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